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Cumulative Damage and Crack Growth in Solid Propellant

C. T. Liu

February 1997

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Phase I Final Report

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FOREWORD

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This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the SF Form 298.

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13. ABSTRACT (MAXIMUM 200 WORDS)

This report covers results of research addressing the fracture and crack growth behavior of solid propellants in support of structural integrity methodology for the failure response of solid propellant rocket motors. The effects of damage, temperature, and strain rate on local behavior near the crack tip and crack growth behavior in solid propellants were investigated. Numerical modeling techniques were used to determine the local strain fields near the crack tip and the fracture parameters associated with crack growth. The results of both experimental and analytical analyses were evaluated and discussed.

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INTRODUCTION

There are imperfections existing in solid propellants. These imperfections may be produced during the manufacturing and/or fabrication processes of the propellant grain. In analyzing the strength of the propellant grain, the imperfection may be idealized as a crack in the material. In addition to the idealized crack, large cracks can also develop in the propellant grain during storage, firing, etc. Past experience indicates that cracking does not necessarily lead to catastrophic or unacceptable ballistic performance conditions. Therefore, when determining the ultimate capacity or the ultimate service life of rocket motors, the failure criterion should include the crack propagation aspect of localized failure. In other words, fracture mechanics theory should be incorporated into structural design and service life predictions of solid rocket motors.

Service life extension based on the predicted ultimate service life will ensure that a rocket motor's maximum service use is attained and that the unnecessary phase-out of cracked but still serviceable motors will be avoided. Thus, a considerable cost savings can be achieved. Furthermore, using the advanced technologies in structural design and service life prediction of solid rocket motors can significantly improve the reliability of solid rocket motors.

This report covers four major tasks: Task 1 - nondestructive evaluation of cumulative damage in solid propellants, Task 2 - a probabilistic crack growth model, Task 3 - crack growth models, and Task 4 - numerical modeling. Numerous articles have been published reporting specific accomplishments achieved during this project. This final report does not repeat details contained in these publications, but instead summarizes each of the four major tasks.

TASK 1 - NONDESTRUCTIVE EVALUATION OF CUMULATIVE DAMAGE IN SOLID PROPELLANTS

Task 1 objectives were to use ultrasonic and acoustic imaging techniques to monitor damage initiation and evolution processes as well as to determine the relationship between nondestructive damage parameter and material property.

In the ultrasonic analysis, changes in the relative acoustic attenuation coefficient, $\Delta\alpha$, for longitudinal ultrasonic waves propagating normal to the applied strain have been used as damage assessing parameters to determine the material's damage state. Experimental data [1-3] indicate that $\Delta\alpha$ correlates well with secant modulus, volume dilation, and dissipated energy.

Experimental data also indicate that the cyclic stress-strain curves exhibit the typical phenomena of the strain-induced stress softening known as the "Mullins Effect" commonly observed in the polymeric materials and solid propellants. The degree of stress softening depends on the cyclic loading sequence. When the specimen is cycled between 0% and 21%, as compared with the lo-hi load sequence, the hi-lo sequence produces a significantly higher reduction in stress between the first and second strain cycles. In addition, the increase in the number of strain cycles in each strain block of the cyclic loading can lead to a relatively higher material softening. Also, the simple rate-independent damage function depends on the cyclic loading sequence. Experimental findings reveal that cyclic loading produces a cyclic behavior and cumulative effect on $\Delta\alpha$, and a good correlation exists between $\Delta\alpha$ and the material's constitutive behavior. In addition, the cyclic loading sequence has a significant effect on $\Delta\alpha$. It is found that the maximum value of $\Delta\alpha$ for the hi-lo load sequence is approximately two times higher than that for the lo-hi load sequence, and the slope of the $\Delta\alpha$ versus ε curves for the hi-lo load sequence is steeper than that for the lo-hi load sequence.

In the acoustic imaging analysis,[4-8] experimental results indicate that damage occurred near the crack tip and, initially, the damage zone's shape was very similar to the plastic zone's shape near the crack tip in metals. However, when the strain level was increased, the damage zone's shape became irregular. Experimental results from the cyclic tests revealed that damage zone size and intensity of damage were highly dependent on time and load history. Therefore, exercise caution when interpreting the acoustic imaging results or other nondestructive testing results to determine the damage state in solid propellants. In addition, a comparison of the results of the finite-element analysis with the results of the

acoustic imaging test reveals that the damage distribution is roughly commensurate with the stress distribution in the specimen.

TASK 2 - PROBABILISTIC GROWTH MODELS

The objective of this study was to develop crack growth models based on probabilistic mechanics and fracture mechanics. It is well known that, on the microscopic scale, a highly filled solid propellant can be considered to be a nonhomogeneous material. Therefore, it is expected that the local stress and strength will vary in a random fashion. Consequently, it is reasonable to expect that the failure location will also vary in a random manner. In addition, since the failure of the material is closely related to the damage state and since the damage process is a time-dependent process, it is expected that the failure time will also vary randomly. Thus, from a probabilistic viewpoint, the failure site and the associated failure time can be considered to be random variables. Therefore, in order to obtain a fundamental understanding of crack growth behavior in solid propellants, it is desirable to develop a crack growth model based on probabilistic mechanics. With this in mind, a probabilistic model[9] that indicated that a power law relationship exists between crack growth rate and the Mode I stress intensity factor (K_I) was developed. Subsequently, the developed crack growth model was refined[10] to increase its range of applicability.

The sensitivity of crack growth rate to the variation of the parameters in the crack growth model was investigated and the limitations and applicability of using the model to predict were determined. It was found that the power law relationship between the crack growth rate and the Mode I stress intensity factor was supported by experimental data. In addition, among the parameters, α and β of the Weibull distribution of strength and b and g of the damage function, it is the characteristic strength β that has the greatest effect on the crack growth rate. Also a good prediction exists between the theoretically predicted and the experimentally measured crack growth rate.

TASK 3 - CRACK GROWTH MODELS

The objectives of this study were: (1) determine the effects of temperature, strain rate, and preload (or predamage) on the crack growth behavior in solid propellants, and (2) develop crack growth models.

In this study, the effects of temperature (-65°F, 72°F, and 165°F) and strain rate (0.05 and 0.25 min^{-1}) on microstructural damage, fracture processes at the crack tip, and crack growth behavior were investigated[11-18]. Fracture in solid propellants was observed to be associated with a damage mechanism involving highly localized deformation leading to the development and growth of microvoids. Crack advancement occurs as the fibrils at the trailing end of the failure process zone fracture and the voids coalesce with the crack tip. The basic damage mechanism is the development of microvoids or micro-cracks in the binder or binder/particle separation known as dewetting. The time-dependent process of dewetting nucleation, due to the time-dependent processes of stress redistribution and binder/particle separation, is the main factor responsible for time-dependent crack growth behavior.

The effect of temperature on fracture toughness was investigated. Fracture toughness at -65°F was significantly larger than at either 72°F or 165°F even though the failure process zone size at -65°F was smaller than that at either 72°F or 165°F. This indicates that the toughening mechanisms at different temperatures are different. The increase in fracture toughness at -65°F is believed to be due to the increase in bond strength at the particle/binder interface and in binder strength as well as to the compressed ability of load distribution. Experimental data also revealed that the variation in strain rate (0.05 and 0.25 min^{-1}) did not appear to cause distinct changes in the extent of microstructural damage.

The effect of specimen thickness on crack growth behavior was also investigated. At -65°F, maximum K_I value is 40% greater for the thick specimen than for the thin specimen. This is expected to be due to a change in the mechanism. At -65°F, the thick specimen develops transverse constraints which not only embrittle the specimens, as in metal, but also make the specimen stronger. This occurs because a shift occurs in the crack growth mechanism from the blunt-grow-blunt-grow process to a classical brittle fracture. The ability of thick specimens to redistribute stresses allows much greater stresses to develop, thus, a greater K_I. However, at 72°F, the maximum value of K_I is about 25% less in the thin specimen than in the thick specimen. Such an effect is well known in metals and is due to transverse constraints in

thicker specimens. However, in solid propellants, the effect is assumed to be due to development of the failure process zone at the crack tip. The relatively larger failure process zone in the thin specimen results in a higher K_I in the thin specimen than in the thick specimen.

In the preload (or predamage) analysis, a 3-6-9% strain cycle was applied to the specimens to induce damage in the material. Experimental data revealed that for displacements less than the maximum displacement, U_{max}, a considerable amount of stress softening occurs. When the displacement approaches and exceeds U_{max}, the difference between the virgin and the preload-displacement curves becomes small. Since the crack growth behavior is controlled by the local stress at the crack tip, which is in turn closely related to the applied load, it is expected that preload has a similar effect on crack growth behavior. Experimental data revealed that the stress intensity factor, K_{Ii}, corresponding to the onset of crack growth is considerably smaller for the preload specimen than for the virgin specimen. The effect of preload on the magnitude of K_{Ii} seems to decrease with increasing loading rate. Experimental data also revealed that the effect of preload on crack growth behavior depends on the applied loading rate.

TASK 4 - NUMERICAL MODELING

The objectives were: (1) to investigate the effect of crack-defect interaction on local stress near the crack tip, (2) to determine fracture parameters at crack tips, and (3) to determine the range of using linear fracture mechanics theories to characterize crack growth behavior. In this study, both linear and nonlinear numerical modeling analyses were conducted. In the linear analysis, a three-dimensional elastic analysis of crack-defect interaction was conducted using finite element methods[19-20]. The results of the finite element analysis reveal that, depending on the size and location of the defect, the presence of a defect can change the magnitude and distribution of stress intensity factor along the crack front and can significantly affect the stress distribution in the defect-affected zone. The size of the defect-affected zone depends on the thickness of the defect; the thicker the defect the greater the size of the defect-affected zone. The result of the analysis also revealed that, in order to stimulate a void the modulus of the defect element should be set equal to or less than 0.001 psi. For the cases considered, the presence of a void affects only the stresses in the adjacent elements and produces a negligible effect on the magnitude and distribution of K_I along the crack front. In addition, the magnitudes of K_I are highly dependent on damage intensity in the immediate vicinity of the crack tip and they are relatively insensitive to the damage state away from the crack tip. However, the damage gradients have a relatively large effect on the stress distributions away from the crack tip.

In the nonlinear analysis, a simple three-dimensional phenomenological nonlinear constitutive model[21] has been developed to model particulate composites such as solid propellants undergoing damage. The constitutive model is motivated by results of a micromechanical model based on Eshelby's equivalent inclusion analysis and Mori-Tanaka's method for an elastic composite undergoing damage either by debonding or cavity formation. The constitutive model is implemented in a finite element code (FEAP) and was used to study cracktip behavior in solid propellants. Crack growth behavior in edge cracked fracture specimens subjected to a constant crosshead speed was simulated. Finite element modeling[22] revealed that cracks in these specimens undergo blunting prior to growth. The nonlinear or the damage region (process zone) is localized near the crack tip and has dimensions on the order of 0.1-0.2% of the crack length prior to crack initiation and growth.

The modeling of fracture behavior reveals that linear fracture mechanics (LFM) can be used to predict fracture behavior of laboratory solid propellant specimens, and crack growth is probably governed by local critical normal strain or volume dilatation to failure. The cracktip strain and displacement fields also reveal that outside the process zone LFM holds.

A small scale computational damage analysis is performed to establish the relationship between applied loading and extent of the nonlinear process zone or local damage region near the crack tip. A circular region (radius, R) containing an edge crack of length R is subjected to boundary displacements corresponding to the Mode I stress intensity (K_I) field corresponding to the material properties (E and ν) of a propellant. The nonlinear damage model is applicable for the entire domain. The far field K_I is increased gradually and the size of the nonlinear zone is established. The loading is applied so that the size of the nonlinear zone (r_D) is small when compared with the size of the computational domain

($r_D << R$). From our analysis it appears that the relationship between the size of the process or damage zone and applied stress intensity, K_I, is $r_D \cong 0.4\ (K_I\ \sigma_0)^2$ where σ_0 is the failure or ultimate stress from the uniaxial stress experiments. In analyzing solid rocket motors, it appears that as long as the characteristic dimensions are much greater than r_D, then the use of LFM may be valid.

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Appendix A

AIAA Paper 86-1015

Effect of Load History on the Cumulative Damage in a Composite Solid Propellant

C.T. Liu
Air Force Rocket Propulsion Laboratory
Edwards Air Force Base, California

J.L. Bellin
R.W. Holsinger
Lockheed Research Laboratory
Palo Alto, California

Abstract

The effect of Strain Rate and cyclic loading on the cumulative damage in an inert composite solid propellant were investigated. Recorded mechanical and acoustic response data were both used to calculate the stress and the changes in the relative acoustic attenuation coefficient and the volume dilatation as a function of strain. The characteristic of internal damage, measured in terms of acoustic attenuation, were determined. The results of the experimental data and the effects of cyclic loading and strain rate on the cumulative damage model under constant strain rate condition was developed and the applicability of using this model to predict damage was discussed.

Proceedings of the AIAA/ASME/ASCE/AHS 27th Structures, Structural Dynamics and Materials Conference, 1986.

Appendix B

Effects of Cyclic Loading Sequence on Cumulative Damage and Constitutive Behavior of a Composite Solid Propellant

C.T. Liu
Air Force Rocket Propulsion Laboratory
Edwards Air Force Base, California

Abstract

This paper will discuss the internal damage state in a composite solid propellant subjected to two different cyclic loading sequences which were measured using an ultrasonic technique. Both recorded mechanical and acoustic response data were used to calculate the stress and the changes in the relative acoustic attenuation coefficient as a function of strain. The results of the experimental data were evaluated and the effects of loading sequence on cumulative damage, constitutive behavior. and residual strength are discussed.

Proceedings of the AIAA/ASME/ASCE/AHS 28th Structures, Structural Dynamics, and Materials Conference, AIAA, New York, April 1987

Appendix C

Acousto-Ultrasonic Technique Applied to Filled-Polymer Damage Assessment

B. Tang
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Phillips Laboratory
Edwards Air Force Base, California

E.G. Henneke II
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

Abstract

An acousto-ultrasonic technique was used to assess cumulative damage in filled polymers. Advantages of the technique include 1) high sensitivity, permitting the detection of early damage processes, 2) fast response, permitting rapid and automated inspection, and 3) need for access to only one surface of the test article. Two kinds of tests -- fracture and loading-unloading tests -- were performed on filled-polymer specimens. In these tests, the energy content and central frequency of acousto-ultrasonic signals were obtained. The acousto-ultrasonic technique can be used to determine the damage state in filled polymers.

Journal of Spacecraft and Rockets, Vol. 32, No. 5, September-October 1995

Appendix D

Measurement of Damage in a Solid Propellant by Acoustic Imaging Technique

C.T. Liu
Air Force Astronautics Laboratory
Edwards Air Force Base, California

Abstract

The damage state in composite solid propellant specimens subjected to different loading histories was investigated using acoustic imaging techniques. The acoustic imaging data were analyzed to delineate the damage field in the specimen and to generate contour plots of the damage intensity. The results of these analyses were compared, and the effects of the loading history and crack length on damage characteristics are discussed.

Material Evaluation, Vol. 47, June 1989

Appendix E

Investigating the Crack Stress Shielding Effect by Using Photoelastic and Acoustic Imaging Techniques

C.T. Liu
Air Force Astronautics Laboratory
Edwards Air Force Base, California

C.W. Smith
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

Abstract

In this study, the values of Mode I stress intensity factor at the tip of the center crack in pre-cracked specimens were determined by using the photoelastic method. The pre-cracked specimens were made of the binder material of a composite solid propellant. Two types of pre-cracked specimens with three cracks and one crack, respectively, were studied. Experimental results indicated that the existence of the upper and the lower cracks produced a shielding effect on the center crack. The degree of the shielding effect depends on the relative lengths of the center crack and the other two cracks. In addition to the photoelastic analysis, an acoustic imaging technique was used to determine the damage fields in the composite solid propellant. The results of the acoustic imaging tests and the photoelastic tests were compared and the effects of the two materials on the shielding effect are discussed.

Optics and Lasers in Engineering 0143-8166/91/$03.50
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Appendix F

AIAA Paper 88-2284

Evaluation of Damage Fields Near Crack Tips in a Composite Solid Propellant

C.T. Liu
Astronautics Laboratory (AFSC)
Edwards Air Force Base, California

Abstract

The damage characteristics in precracked composite solid-propellant specimens subjected to a complex cyclic loading history are investigated using acoustic imaging techniques. The acoustic imaging data are analyzed to delineate the damage field ahead of the crack tips and to generate contour plots of the damage intensity. The results of these analyses are compared and the effect of loading history on damage characteristics is discussed.

Proceedings of the AIAA/ASME/ASCE/AHS 29th Structures, Structural Dynamics, and Materials Conference, April 1988

Appendix G

Acoustic Evaluation of Damage Characteristics in a Composite Solid Propellant

C.T. Liu
Phillips Laboratory
Edwards Air Force Base, California

Abstract

This paper summarizes the current progress in characterizing the damage field near the tip of a crack in a composite solid propellant, using the acoustic-imaging technique. The effects of loading history on the damage characteristics near the crack tips are discussed. In addition, the limitations of the acoustic-imaging technique are discussed, and recommendations for future work are presented.

Journal of Spacecraft and Rockets, Vol. 29, No. 5, September-October 1992

Appendix H

Investigation of Damage Initiation and Evolution in a Particulate Composite Materials

C.T. Liu
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Edwards Air Force Base, California

Abstract

The damage characteristics near the crack tip in a highly filled polymeric material subjected to a simple incremental strain history were investigated using acoustic imaging technique. The acoustic image at a given applied strain level was plotted in the form of iso-intensity contours of the transmitted acoustic energy to enhance the resolution of the damage field. The experimental data were analyzed and the effect of the applied strain level to another strain level and the increase from one applied strain level to another strain level on the damage characteristics were determined. In addition, a general damage evolution model was developed and the expected results from such a model were discussed.

Computational Mechanics publication, Ashurst Lodge, Ashurst Southhampton S040 7AA, UK, 1994.

Appendix I

Probabilistic Crack Growth Model for Application to Composite Solid Propellants

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Abstract

In this study a crack growth model, based on probabilistic mechanics, is developed. The developed crack growth model yields a power law relationship between the crack growth rate and the Mode I stress intensity factor. The sensitivity of the crack growth rate to the variation of the parameters in the crack growth model is investigated and the results are discussed. The limitations and the applicability of using the developed crack growth model to predict crack growth behavior are also discussed.

Journal of Spacecraft and Rockets, Vol. 31, No. 1, January-February 1994

Appendix J

Investigating the Effect of Damage Function on Probabilistic Crack Growth Model

C.T. Liu
Phillips Laboratory
Edwards Air Force Base, California

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Irvine, California

Abstract

In this study, the effect of damage function on the probabilistic crack growth model was investigated. For the damage functions considered, a power law relationship exists between the crack growth rate and the Mode I stress intensity factor. A parametric study was conducted to investigate the effect of varying crack growth model parameters on crack growth rate. The results of the analysis are discussed.

Computational Mechanics publication, Ashurst Lodge, Ashurst Southhampton S040 7AA, UK, 1994.

Appendix K

Critical Analysis of Crack Growth Model

C.T. Liu
Air Force Astronautics Laboratory
Edwards Air Force Base, California

Abstract

During the past years, a considerable amount of work has been done in studying the crack growth behavior in composite solid propellant. Experimental findings indicate that a power law relationship exists between the crack growth rate and the Mode I stress intensity factor. The usefulness of this relationship depends on how accurately this relationship describes the crack growth behavior in the material. Since the crack growth rate and the stress intensity factor are calculated from measured quantities, they are subjected to measurement error and data scatter. Therefore, it is the purpose of this study to review the factors that affect the accuracy and the scatter of the crack growth data and to examine the characterization of the statistical feature of the crack growth behavior.

Journal of Propulsion, Vol. 6, No. 5, September-October 1990

Appendix L

Crack Growth Behavior in a Composite Propellant with Strain Gradients -- Part II

C.T. Liu
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Edwards Air Force Base, California

Abstract

The crack growth behavior in a highly filled composite propellant with strain gradients was studied through the use of centrally cracked, wedge-shaped sheet specimen. The specimens were tested under a constant strain rate condition at room temperature. Two crack lengths were considered. The experimental data were analyzed to calculate the instantaneous stress intensity factor K_I and the associated instantaneous crack growth rate *da/dt*. In the data analysis, four data processing methods--the secant method, the modified secant method, the spline fitting method, and the total polynomial method--were considered. The effect of the data processing method and the time interval for crack length measurement on the accuracy of the calculated crack growth rate was investigated. In addition, the effect of the initial crack length, the nonuniform gross strain field, and the data processing method on the crack growth behavior was also investigated, and the functional relationship between the stress intensity factor and the crack growth rate was determined.

Journal of Spacecraft and Rockets, Vol. 27, No. 6, November-December 1990

Appendix M

Effects of Near-Tip Behavior of Particulate Composites on Classical Concepts

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Abstract

The principles of classical fracture mechanics, especially linear elastic fracture mechanics (LEFM) including small-scale yielding, are well established for single-phase materials. In recent years, much development and use of polyphase (composite) materials has led to the application of fracture mechanics to such materials. In this paper, the effects of embedding hard particles in a soft matrix upon the opening, growth and stress intensity factor (SIF) of cracks in a particulate composite are studied from a combination of surface measurements and a "first-cut" three-dimensional finite element model, the latter for assessing the projection of the observed surface effects in the thickness direction.

Composite Engineering, Vol. 1, No. 4, pp. 249-257, 1991. Printed in Great Britain

Appendix N

Investigating the Near-Tip Fracture Behavior and Damage Characteristics in a Particulate Composite Material

C.T. Liu
Phillips Laboratory
Edwards Air Force Base, California

Abstract

In this study, the local fracture behavior and damage state near the crack tip in a particulate composite material were investigated through the use of precracked sheet specimens. The specimens were subjected to a simple incremental strain history at room temperature. During the test, a high-energy real-time x-ray system was used to record the x-ray data and the fracture process near the crack-tip region. The experimental data were analyzed and the results were analyzed and the results are discussed.

ASTM, STP 1189, 1993

Appendix O

An Experimental Study of the Loading Rate Effect on the Crack Growth Behavior in a Composite Solid Propellant

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Edwards Air Force Base, California

Abstract

The crack growth behavior in a highly filled composite solid propellant was studied through the use of a centrally cracked strip biaxial specimen. The specimen was tested under a constant crosshead speed at room temperature. In this study, three different crosshead speeds and two different crack lengths were considered. During the experiment, a video camera was used to monitor the crack growth and a tape-recorder was used to record the load as a function of time. The raw experimental data (crack length, load, time) together with a response surface equation (relating the normalized stress intensity factor to the two half crack lengths) were used to calculate the instantaneous crack growth rate and the associated stress intensity factor. The experimental data were analyzed to investigate the effect of crosshead speed on the crack growth behavior in the material. In addition, the local fracture behavior near the crack tip was also investigated and the results were discussed.

Journal of Reinforced Plastics and Composites, Vol. 12, January 1993
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Appendix P

Effect of Predamage on Crack Growth Behavior in a Particulate Composite Material

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Abstract

The effects of predamage and strain rate on the crack growth behavior in a highly filled polymeric material were investigated. Centrally cracked predamaged sheet specimens were used to conduct crack propagation tests under two strain rates (0.05 and 5 min^{-1}) at room temperature. Experimental data were analyzed, and crack growth resistance curves as well as crack propagation curves, shown as the crack growth rate as a function of Mode I stress intensity factor were plotted. It is found that the crack growth behavior in predamaged specimen is highly dependent on the strain rate.

Journal of Spacecraft and Rockets, Vol. 32, No. 3, May-June 1995

Appendix Q

Local Fracture and Crack Growth Behavior in a Particulate Composite Material

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Abstract

In this study, centrally cracked sheet specimens made from polybutadiene rubber embedded with hard particles were used in cracked propagation tests. The precracked specimens were tested at two constant crosshead speeds, 0.58 mm/min and 50.8 mm/min, at room temperature. The effect of crosshead speed on the local fracture and the crack behaviors were investigated and the results are discussed.

Journal of Reinforced Plastics and Composites, Vol. 15, February 1996
0731-6844/96/02 $10.00/0

Appendix R

Temperature and Rate Effects on Stable Crack Growth in a Particulate Composite Material

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Abstract

In this study, edge cracked sheet specimens made from polybutadiene rubber embedded with hard particles were used in crack propagation tests. Crack propagation tests were conducted under two crosshead speeds (2.54 mm/min and 12.7 mm/min) at three temperatures (-53.9°C, 22.2°C, and 73.9°C). These experimental data were analyzed and the crack growth resistance curves and the crack growth rate versus the Mode I stress intensity factor were plotted. Based on these experimental results, the effects of temperature and loading rate on the crack growth behavior were investigated and the results are discussed.

Experimental Mechanics, Vol. 36, No. 3, September 1996

Appendix S

AIAA Paper 89-2646

Numerical Modeling of Crack-Defect Interaction

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Abstract

An elastic analysis of the interaction between a main crack and defects was conducted using finite element methods. In the analysis, two different types of defects, voids, and damage were considered. The effects of the size, the location, and the number of voids, and, also, the intensity of damage on the Mode I stress intensity factor and the stress distribution near the crack tip region, were discussed.

Proceedings of the AIAA/ASME/ASME/SAE 25th Joint Propulsion Conference, July 10-12 1989.

Appendix T

AIAA Paper 90-0927

Three-Dimensional Finite Element Analysis of Crack-Defect Interaction

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Abstract

A three-dimensional elastic analysis of crack-defect interaction was conducted using finite element methods. The defect was modeled by setting the Young's modulus of the defect material equal to 0.1 psi. The effects of the size and the location of the defect and the distribution of the Mode I stress intensity factor along the crack front and the stress distribution near the crack tip are evaluated and the results are discussed.

Proceedings of the AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Long Beach CA, April 2-4 1990

Appendix U

Modeling Constitutive Behavior of Particulate Composites Undergoing Damage

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Abstract

A simple rate-independent phenomenological constitutive model is developed for particulate composites undergoing damage. The constitutive model is motivated by the results of a micromechanical model based on Eshelby's equivalent inclusion analysis and Mori-Tanaka's method for elastic composite undergoing damage either by debonding or cavity formation. The micromechanical model is used to illustrate the behavior of a composite consisting of hard particles reinforcing a soft, nearly incompressible elastic matrix. The composite is assumed to behave linearly elastic in the absence of any damage. The damage accumulation is described by a single scalar internal variable, the maximum volume dilatation attained during the deformation process. Two damage functions govern the degradation of the bulk and the shear moduli in the phenomenological constitutive model. Corresponding computational algorithmic tangent moduli is derived and examples are provided to illustrate the versatility of the proposed model.

International Journal of Solids Structures, Vol. 32, No. 6/7. pp. 979-990, 1995

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Appendix V

Effect of Loading Rate on Crack Tip Behavior –
An Experimental and Numerical Investigation

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